Equipment Maintenance and Replacement

Decision Making Processes

A Senior Project

Submitted to

the Faculty of California Polytechnic State University,

San Luis Obispo

In Partial Fulfillment

of The Requirements for the Degree of

Bachelor of Science in Industrial Engineering

By

Michael W. Gage

March, 2013

ABSTRACT

Equipment Maintenance and Replacement

Decision Making Processes

Michael W. Gage

This project contains recommendations for the decision making processes for support and production equipment maintenance and replacement for a large defense contractor. Recent literature has been reviewed to provide perspective on current trends in the field. A complete evaluation of their current processes and systems is included with recommendations on areas for improvement. A decision support system is also proposed to supplement their existing decision making.

Keywords: decision support system, maintenance, replacement, decision making

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Introduction

Many companies have equipment used in production and testing that needs to be regularly maintained or replaced. A large defense contractor, Company X, has many advanced pieces of production equipment that support its operations. These pieces of production equipment operate in conjunction with support equipment. Breakdowns can cause a variety of issues. In some cases, they occur in support equipment when the production equipment is not in use. Lead times in obtaining replacement parts or extended repair time can cause outages that delay production, and result in missed deadlines. These can have severe impacts in the short-term for lost award money from current contracts, and in the long-term will reduce the number of contracts and programs. Company X has requested a review and recommendations on the current support equipment maintenance and replacement processes to prevent excess work or costly breakdowns.

Background

Company Information

Company X is part of a larger global security and information technology corporation. It has four major operating units that focus on business areas.

Company X has locations across the United States, including both the East and West Coast and two main locations. The company has major business areas including missile defense systems, advanced research and development and exploratory, sensory, surveillance, navigation, and communications satellites. These business units support programs operating on intercontinental ballistic missiles, missile defense platforms, and a wide variety of satellite technology, including missile launch early warning systems, military imaging and communication, weather imaging, video and voice communications, GPS, and exploration imaging of outer space. At both their main facilities, there is a wide variety of specialized production and support equipment used in the design, manufacturing, and testing of the different products the programs produce. Systems can range in complexity from a simple crane to some of the most advanced test chambers in the United States for thermal, pyro-shock, atmospheric, audio, and vibration testing.

In the summers of 2009 and 2010, I had the unique opportunity to intern at Company X working in operations supporting the facilities. In 2009, I helped with a variety of business needs including workspace planning, a workspace utilization audit, business unit specific requests, and process improvement. In 2010, I worked on several maintenance systems and procedures. I redeveloped the user interface and relationship design for the Facility Infrastructure Condition Assessment (FICA) database. I assisted in validating over 1400 records in the transition from a hierarchical to a relational database for maintenance. Company X offered the current project based my experiences to examine and improve their processes for maintenance and replacement of production and support equipment. They provided a laptop computer and an RSA token for VPN access to their network and systems in support of the project.

Literature Review

In the late 1970's, maintenance of the latest commercial aircraft was becoming a more pressing issue for many airlines. United Airlines (UAL) recruited two employees, F. Stanley Nowlan and Howard Heap, to create a report detailing what would need to be done for maintenance focusing on the reliability of aircraft over time. The report was to focus on problems with the new Boeing 747. They published a report sponsored by the Department of Defense (DOD) titled *Reliability Centered Maintenance* in 1978. This report was the first of many articles about reliability centered maintenance (RCM) and the importance of maintenance for the sake of reliability, instead of maintenance for the sake of liability. One of the most important findings within this report is the lack of correlation between failures and the age of specific airplane components. A common misconception in maintenance is that as a product ages it will need more maintenance. This is not necessarily true, and in some cases, products need more maintenance earlier in their lifecycle. The report calls for maintenance based on the business impact caused by a failure, with a clear definition of types of failure and what would be classified as a failure.[1]

The *NASA Reliability Centered Maintenance (RCM) Guide For Facilities and Collateral Equipment* has an in-depth discussion of various aspects of reliability centered maintenance directed towards the assets NASA uses in production. One main point of the report is categorizing the four types of maintenance: reactive, preventative, predictive, and proactive. The report discusses where RCM is appropriate and a variety of decision making tools for maintenance decisions. This guide has been used since 1996 and has been revised several times up to the current 2008 revision. The operations NASA describes are related to facilities and equipment very similar to the assets of Company X in its two main locations. (There are very few published standards for spacecraft facilities maintenance procedures due to the classified nature of many programs.)[2]

"Constructing and Maintaining Detailed Production Plans: Investigations into the Development of Knowledge-Based Factory Scheduling Systems" provides a comprehensive discussion of managing the many constraints related to factory scheduling. Although the discussion is mostly about facilities that mass produce individual products and dealing with frequent production changeovers, the discussion is directly relevant to manufacturing resources in restricted areas with a fixed process flow. Some of the important restrictions in a manufacturing environment discussed include causal or process related (order of operations), physical or station related, and resource unavailability. With the restrictions, there are also many goals for optimization including meeting due dates, minimizing work in progress (WIP) time, maximizing resource utilization, and maintaining shop stability with changeovers. Keeping the restrictions and goals in mind, a variety of approaches can be taken to satisfy the needs of the problem accounting for many variables in the process.[3]

"An enhanced approach for implementing total productive maintenance in the manufacturing environment" discusses the use of Total Productive Maintenance (TPM). The article gives several reasons to use TPM, most importantly the impact on the bottom line of production losses. One main concept is overall equipment effectiveness, which looks at availability, performance efficiency, and the process output quality rate. In addition to the information about TPM, the article recommends other tools to assist in the effectiveness of TPM including life-cycle cost analysis (LCCA), reliability and maintainability predictions/estimation, failure mode, effects, and criticality analysis (FMECA), maintenance task analysis (MTA), level of repair analysis (LORA), reliability centered maintenance (RCM), and maintenance data collection, analysis, and corrective-action system (MDCAS).[4]

"Maintenance management in Italian manufacturing firms" investigates the importance of manufacturing firms to the Italian economy, and the embedded importance of maintenance for creating job opportunities. The study included a wide variety of different Italian firms of varying size and complexity of business operation. The results from the study show many interesting trends, including the decision by many organizations to contract maintenance work out to other organizations, either maintenance focused businesses or the original manufacturers of the equipment. Only 6% of companies have integrated maintenance into their business. Preventative maintenance is also shown to be greatly beneficial in firms of all sizes, and easiest to implement in smaller firms. Predictive or preventative maintenance using condition assessments was demonstrated to be extremely effective. TPM shows improvements as far as quality and safety but does not have a statistically significant impact on costs. Fire-fighting was a common maintenance plan, which is overused and has been proven not to be effective.[5]

"Maintenance resources optimization applied to a manufacturing system" provides a practical approach to applying availability analysis and dependability analysis to assess equipment based on limited maintenance resources and costs as well as redundant systems. The article uses an advanced mathematical model to provide a specific application to management of maintenance resources and equipment availability. Some of the methods of application that are described have been used on a variety of problems including nuclear power plants, redundancy allocation, reparable parallel-series systems, mechanical components, and safety systems. All of the methods are based on a Genetic Algorithm that uses generations, population size, mutation probability, crossover probability, and inversion probability. These parameters are used as inputs to the search algorithm to find the optimal application of maintenance resources. The algorithm mimics the ideal of genetic evolution with the parameters to progressively improve the solutions over so-called generations.[6]

"A Genetic Algorithm Based Approach for Scheduling of Dual-Resource Constrained Manufacturing Systems" proposes an alternative approach to the application of a Genetic Algorithm to scheduling. The alternative looks at both the workers and the machines as constraints. Although the discussion is focused on different operations and workers of different skills, it could be applied to the idea of maintenance as one operation on a machine schedule which has to be fit into the order of processing tasks. The availability of the workers and the machines are both constraints in terms of maintenance in the same way they are constraints in production.[7]

"Applying data mining to manufacturing: the nature and implications" provides a perspective on the possible use of data mining to improve equipment maintenance procedures. Data mining involves the process of going though large amounts of data using preprogrammed logic looking for both high level and low level trends. According to the article, data mining can be used in discovery for patterns within data or for prediction using classification and association rules. There are 12 main classes of techniques for data mining. The IBM seven step data mining procedure is recommended, using a closed-loop feedback system to continuously improve the data mining. Data mining is considered to be an opportunity in manufacturing, but there are some drawbacks and challenges preventing its widespread use. Manufacturing researchers are not familiar with data mining and data mining researchers are not familiar with manufacturing. The few researchers skilled in both do not have access to the sensitive information and the measurability of data mining as an effective tool in a manufacturing environment is lacking. These are all roadblocks to the successful use of data mining in manufacturing. There are also two case studies, one focusing on machine health mining and the other on predicting assembly quality. The largest benefit data mining can provide is a wide search for information with a highly detailed focus on specific issues.[8]

"An object-oriented decision support system for maintenance management" explains how object-oriented programming can be applied to maintenance. Object-oriented programming attempts to create “objects” which have attributes similar to real world objects. An example of this would be a car, which has tires, an engine, a paint color and other attributes. A programming object representing a car would have data fields related to each component object. The focus of an object-oriented approach in manufacturing is to model a system or component individually so each piece of equipment can be viewed as a single object. Object-oriented programming lends itself well to a hierarchy, with data abstraction, encapsulation, inheritance, and polymorphism to adequately describe a wide variety of equipment very easily. The combination of a relational database and objects can create a powerful tool that can be sorted, filtered, and searched quickly in multiple ways. Outside of the object-oriented approach, a decision support system takes previous knowledge in a digital form into account when decisions need to be made. A benefit to a decision support system is the ability to come up with an optimal solution for a decision based on a single criterion, multiple criteria, or a specific approach to the decision. Using a decision support system, all of the optimal solutions can be listed with the method used to generate the solution. Management can choose from the alternatives rather than having to return to generate further alternatives.[9]

"An empirical investigation on the relationship between business and maintenance strategies” looks at the effects of maintenance strategy on the overall business strategy. According to the article, strategy provides direction, integrity, and purpose. At the business level, it identifies several different classifications of strategies including cost leadership, differentiation, and product focus. Maintenance is typically viewed as reactive, proactive, and aggressive. Maintenance has frequently been identified as a part of operations or manufacturing and housed underneath one of those two main areas. However, this article identifies the need for maintenance to be considered as a separate value added activity that is crucial to influencing the success of the business strategy. A study was performed with 150 companies from Belgium and Norway to determine if there is any distinct correlation between maintenance and business strategies. The study was able to decisively conclude that companies who were focused on quality had more pro-active maintenance and better planning and control systems. Companies' business strategies drove them to be more effective in maintenance or their effectiveness in maintenance drove them to adopt a quality focused business strategy. Either way, the identification of this positive correlation can help companies be competitive in a straightforward way by improving maintenance procedures.[10]

"An empirical study of the relationship between production technology and maintenance management" identifies the struggle to effectively perform maintenance with different levels of production technology. The technical complexity, interdependencies, and technical variety of a system can have an effect on the maintainability of a system. Technical complexity is based on the extent to which humans have been replaced with machines. The interdependencies are related to the level of inventory and the use of a "push" system such as Materials Requirements Planning that reduces interdependency versus a "pull" system like Just In Time manufacturing using Kanban cards which increases interdependency. Technical variety is related to the complexity across different workstations throughout the system. Of these factors, technical complexity was the most significant factor that was related to the decentralization of maintenance and the hiring on of professional maintenance staff or payment for outside services. Technical training for staff and the elimination of operator-based maintenance were also trends for technically complex environments.[11]

"System Approached-Based Bayesian Network to Aid Maintenance of Manufacturing Process" looks at a manufacturing system as a network. The network assigns various conditions to each step in the process or each node. The nodes make up an acyclical directed graph, a map which is not self-referential. Each node has probabilities of functioning versus non-functioning states. The network attempts to identify where the failure occurred, looking at internal versus external failures, specifically upstream or downstream node failures. The article provides an example using a lathe and the various states based on the system around the lathe or the network. The entire model is based on the use of Failure Modes, Effects, and Criticality Analysis (FMCEA) and the probability attached to the results of an FMCEA.[12]

"Total maintenance management: a systematic approach" applies continuous improvement to maintenance management. The main idea is asking a series of questions and taking actions to answer the questions. The questions focus on the current state of maintenance management, where the company would like to be, the gap between those two states, and an action taken to bridge the gap. Maintenance management, maintenance operations, and equipment management all play a role in total maintenance management. Organization, training and motivation, and maintenance control are major issues identified for maintenance management. Work measurement and scheduling are major issues identified for maintenance operations. Equipment history, preventative maintenance, predictive maintenance, and asset recognition are major issues identified for equipment management. The specific issues can be targeted with actions to meet continuous improvement goals. The article also focuses on benchmarking. The benchmarking process it recommends is similar to the Define Measure Analyze Improve Control (DMAIC) process. The steps include planning, analysis, integration, action plan, implementation, and further benchmarking. Benchmarking should only occur when the actions taken have the desired results on the maintenance processes.[13]

"The status of maintenance management in Swedish manufacturing firms" provides results from a survey of Swedish companies in different industries about their maintenance planning practices. One finding from the study showed that only 48% of companies had written maintenance polices, while 23% have no strategy at all. The 48% is estimated to be higher than the actual percentage because companies may have considered ISO 9000 an adequate strategy, which is not necessarily enough. Another interesting result was the higher commitment to maintenance issues by production management than production personnel as well as a higher participation in maintenance strategy by production management than production personnel. Production personnel were statistically significantly more invested in maintenance in mechanical engineering industries than in food or chemical industries. 64% of the respondents relied on manual information systems with 9% using integrated automated systems. The majority of time in maintenance is spent on corrective maintenance, with less spent on preventative maintenance, and the least time spent on planning. Fixed interval inspection and corrective maintenance were the most common practices, condition monitoring and maintenance optimization were the least common practices. Organizationally, the firms tended towards a separate maintenance department with 34% of responses and 27% of responses for a joint effort between production and a maintenance department. The article identifies maintenance as a major obstacle in continuous improvement and education of the workforce moving forward. There is room for improvement in maintenance and the opportunity for cost reduction is also present.[5]

"Selecting the most efficient maintenance approach using fuzzy multiple criteria decision making" discusses the use of fuzzy or non-binary logic in determining a maintenance strategy. Fuzzy logic looks at an entire range of numbers such as every number from 0 to 1, not just 0 and 1. Different maintenance approaches can receive a range of capabilities for a situation, which is not just good or bad, but somewhere in between, similar to a decision matrix. The failure itself can also be classified on a range of importance, not only as unimportant or important. The model presented in the article uses past data, current data, and adequacy about each failure mode to assign a membership function, which gives the visual representation of the membership function between 0 and 1 for the failure mode. The model repeats the process for the maintenance procedures. In this particular example, a variety of information is generated using MATLAB to influence the membership functions, and, in turn, the decision that is made about maintenance. The results of the example show that the more knowledge about the failure and root cause, the more effectively a maintenance procedure can be selected which will have the best results on keeping the system functioning.[6]

These articles refer to a wide variety of concepts and studies which have been performed in the field of maintenance. The survey data from the articles helps reveal the lack of maintenance management and the opportunity for improvement at companies worldwide. The many different advanced approaches to mathematically maximizing the value of maintenance offer concrete means to improve a system based on the current state of the system. General concepts such as reliability centered maintenance (RCM), total productive maintenance (TPM), and total maintenance management (TMM), as well as others, offer a framework to approach the analysis of maintaining a system with specific goals in mind. These articles and methods provide a good foundation moving forward with ideas on how to analyze and potentially improve Company X’s maintenance and replacement practices for support equipment.

Current Maintenance Processes

The current maintenance process for support equipment is “ad-hoc” with some oversight through a Maximo SQL database for corrective maintenance and job plans. The current replacement process is managed on a case by case basis with yearly budgets using the FICA database in Microsoft Access. These manual systems of decision making are not easily transferrable to newer generations of maintenance personnel.

Company X uses two separate databases with different pieces of information about equipment. One database has condition assessments used to determine the time-line for replacement. The condition assessment database does not have assessments for every piece of equipment that is maintained. The other database holds maintenance records for both corrective and preventative maintenance. The maintenance database contains all equipment that has been or is currently maintained. This is not all of the equipment that Company X owns, only the portion for which data has been captured. Neither database contains information for all of the equipment.

The database with condition assessments attempts to capture the idea of cooperative or interactive equipment in a few ways. The first way groups equipment using a hierarchical structure of systems and subsystems in specific buildings. A subsystem of equipment may be a set of equipment that operates together or a set of equipment which performs similar tasks. The second means of capturing the interactions between equipment is by nesting some equipment as the components of other equipment. The components and equipment can be the same and all of the same information is recorded about each. In some cases, equipment is recorded in the database both as a component and a piece of equipment. The database with maintenance records does not have any system structure. All equipment is maintained separately, without consideration for the larger system of equipment.

Assessments are not performed on all of the equipment that is maintained. Some pieces of equipment have condition assessments and do not have location or serial number information.

They cannot be located for future assessments and cannot be cross-referenced with the maintenance database. There are some pieces of equipment included in the assessment database, such as building roofs, which are not in the maintenance database.

Figure 1 is a Venn diagram showing the set of all equipment and its existence in the databases.

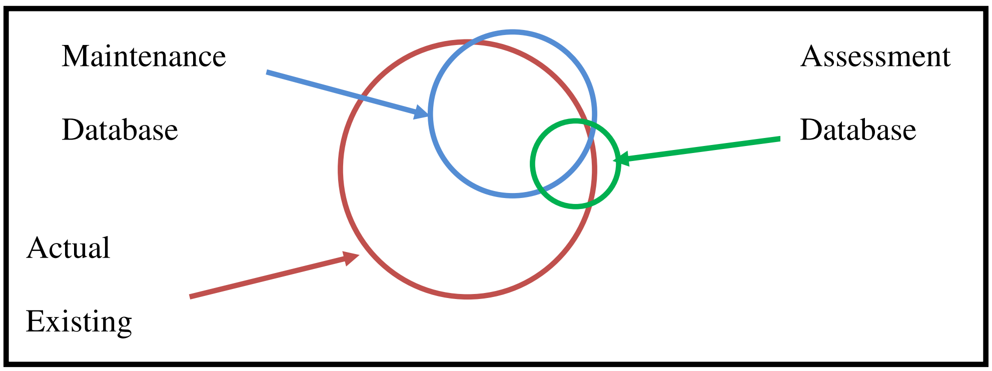

Figure 1: All Company X Support Equipment

Some equipment in the maintenance database cannot be located using the database information. This equipment has scheduled maintenance that is recorded as being completed in the maintenance database and maintenance staff is logging hours working on the equipment. The location information is incorrect in the database but the maintenance staff does not need it to complete their work. Their local knowledge of the equipment exceeds that of the database.

Maintenance is performed on a set schedule, which does not change based on equipment performance. Corrective maintenance is performed when necessary on all equipment, but an increased rate of corrective maintenance does not change the frequency of preventative maintenance performed. Equipment that frequently has down-time is not preventatively maintained more than equipment with little to no downtime.

When equipment is scheduled for maintenance, it is looked at on an individual basis without evaluating its impact on a system. An outage in a high value piece of equipment could be caused by a poorly maintained low value piece of equipment. An outage in many pieces of production equipment can occur due to a breakdown of only a single piece of supporting equipment. There is a lack of leading indicators to show when a piece of equipment might fail. A good example of this is the failure to detect corrosion in a water piping system, leading to a major breakdown of several other systems. An accelerated decrease in the outer wall thickness of a pipe would indicate the need for maintenance or possible replacement.

Two major inhibitors to correcting many of these issues are the lack of maintenance staff to perform preventative and corrective maintenance, and the lack of reliability engineers to perform condition assessments of equipment. The maintenance schedule cannot be met with the available staff, and equipment cannot all be assessed. Current procedures cannot be sustained with the reduced workforce without an increase in the number of failures and an increase in the amount of downtime for equipment.

Current Replacement Processes

The current information used in making the decision to replace equipment includes equipment age, failures which cannot be repaired, current program needs, future strategic plans, and reliability assessments, if available. Some equipment on the site has never been replaced. There are plans forming to gradually replace all equipment of specific types. Recently, many of the power substations have been replaced and upgraded with newer models from the oldest to the newest. Any equipment that cannot be repaired is typically replaced. This could be equipment that requires a complete deconstruction and rebuild, equipment that no longer has spare or replacement parts available, or the lack of a qualified and available technician.

Program needs is one of the most complicated factors in making the decision to replace equipment. Each area within Company X has multiple programs running at a single time. Each program is working on a project for a customer with a single deliverable or a series of deliverables. A common structure for a program includes a bidding process to win a contract, the design of a satellite system, and the production of a series of satellites which follow those specifications. The classified nature of many programs and the variety of customers requires a complete compartmentalization of production facility use, access, and information. Programs receive funding based on the contract and awards based on meeting specific deadlines. Funding from the programs does not necessarily reach the budget of operations and facilities for replacing equipment.

Future strategic planning is also a complicated factor in making the decision to replace equipment. The strategic plans include predictions on future contracts and plans to expand or constrict the footprint of the entire facility. A possible future contract may outweigh the importance of several existing contracts, meaning equipment that would support future operations is replaced prior to equipment that may be needed to complete current contracts.

The reliability assessments, as mentioned with regard to maintenance, are not always available and not regularly updated. The assessments are subjective on a 0-5 scale, 0 being the best condition and 5 being the worst condition. There are many pieces of equipment with the same score but they have a large variation in actual condition.

Once equipment is selected for replacement, a project manager in facilities takes on the project and creates designs with plans and a schedule. A bidding process usually follows with several contracting companies estimating the cost and timeline for the work. Occasionally, the contracting companies also create the designs in the bidding process. The pricing and research for replacement equipment occurs during this process. After a contractor is selected for a portion of or the entire project, the project manager monitors progress and reports weekly to managers. The replacement must be scheduled around the production facilities being actively used by programs. There are often delays associated with scheduling around production.

Design

Using the information from existing research and the background about Company X's existing procedures, a decision support system was designed. Each part of the design provides a quantitative foundation for making decisions about equipment.

Replacement Reasoning

There should be three main reasons why equipment is considered for replacement. The first reason is the equipment is depleted of function. A very common example is oil wells. Once there is no more oil in the ground, the well is depleted. In the case of Company X, this would be considered a piece of equipment that is run-to-failure. These items are low cost reliable equipment like small pumps or fans which either have redundancy or can easily be replaced and are not in critical systems. The next reason for replacing equipment is if the equipment becomes obsolete. The best example of this is a computer. Older computers are much slower and have fewer features than their modern counterparts. In addition, older computers are harder to maintain because replacement parts and qualified technicians are much harder to find. Obsolete equipment for Company X would include manually operated machining equipment. This equipment could be replaced by CNC equipment with better tooling, higher accuracy, consistent precision, and more automation. The safety systems in CNC equipment are also significantly better than manually operated machinery. The last reason for replacement, and also the most frequent, is deterioration due to aging. Any mechanical equipment faces this problem, including cars, airplanes, and bicycles. For Company X, this includes water pipes, cranes, boilers, chillers, ventilation systems, lighting, high bay entrances, chambers, and almost any type of equipment which does not meet the criteria for the previous two reasons. Even with regular maintenance, the cost of maintenance for these items eventually exceeds the cost of replacement.

An alternate reasoning behind the replacement of equipment is to match budget policies. One common policy is that if the budget is not met on a yearly basis, it is reduced accordingly. This presents a potential problem when there is a fluctuation in the amount of equipment which needs to be replaced each year. In years where more funding needs to be spent on replacing equipment, the budget will be insufficient and in the alternate years the budget will continue to decrease. Another common policy is the budget is fixed every year and both over-spending and under-spending carry over year to year. Problems can occur in this scenario when over-spending is recurrent year after year. Good planning can effectively avoid any potential issues with this budgeting policy.

Economic Justification

With a reason to replace equipment, each piece of equipment needs to be evaluated to determine whether the replacement is economically viable. For a piece of depleted equipment, such as a broken pump, it must be replaced immediately, unless there is sufficient redundancy in place. There is no economic analysis needed. If the pump is functional, it would not need to be maintained or replaced. For a piece of obsolete equipment, an economic analysis can be performed to decide whether it is a viable option to upgrade to a newer model. However, the economic analysis cannot be the only factor in the decision for obsolete equipment if the features of a newer model are necessary but will cost more money. For deteriorating equipment, an economic analysis can be used exclusively to determine the point at which the replacement is justified.

To perform an economic analysis for the replacement decision, there needs to be consideration for the existing piece of equipment and any possible replacements. A common model for this analysis is known as the defender-challenger model. The defender is the existing equipment on the property which is in operating condition. The challenger is the best alternative which can be purchased and installed on site. There is a group of challengers for each defender, these challenges are evaluated independently against one another using incremental rate of return analysis to determine the best challenger.

For all comparisons between the defender and challenger, the expected uniform annual cost (EUAC) is used in the analysis. The EUAC is calculated by spreading the maintenance and replacement costs across the expected life of the equipment. Equipment that is kept for a shorter time frame has a higher loss in capital value but lower maintenance, repair, and operating costs. The longer the equipment is kept, the depreciation of the capital value is lower on a per year basis but the maintenance, repair, and operating costs rise. The graph of the total EUAC forms a curve as seen in Figure 2.

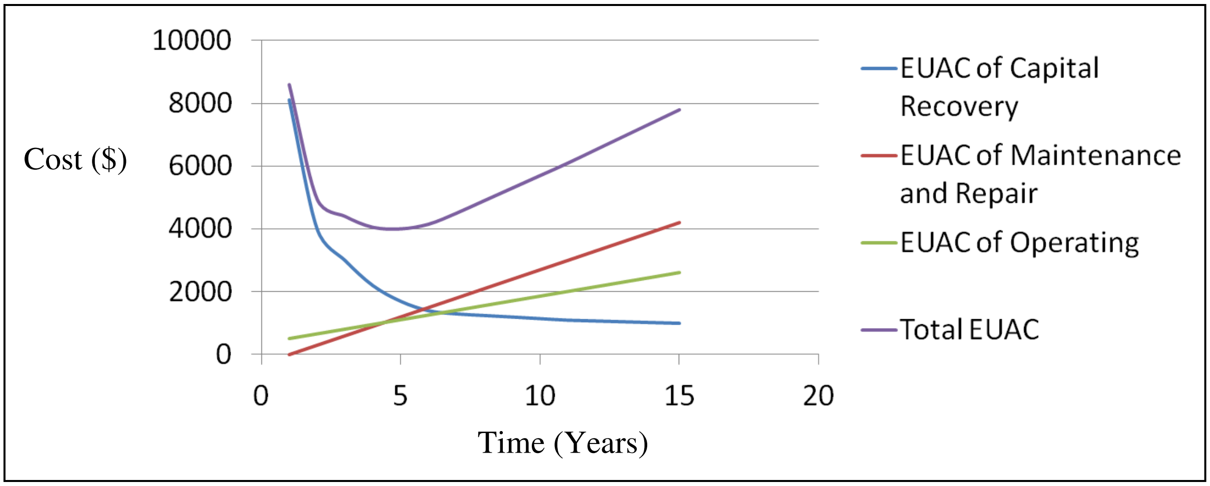

Figure 2: Expected Uniform Annual Cost

If the defender cost data is available and its EUAC is decreasing, the comparison is between the minimum defender EUAC and the minimum challenger EUAC. If the EUAC is increasing, the comparison is between the defender EUAC for the upcoming year and the minimum challenger EUAC. If the data is not available, an estimate of the information over the remaining useful life of the defender is used instead.

Reliability Improvement

With a list of equipment that can be economically justified to be replaced, the next criterion to make replacements is the improvement in reliability. Both the challenger and defender have a measureable reliability. This can be in terms of the expected total life, the expected mean time between failures, or the performance in other applications. The reliability should be measured in the same way for both pieces of equipment.

Replacement Cost for the Year

For each piece of equipment being considered for replacement, the cost of replacing the equipment in the current year's budget must be calculated. This is different than the EUAC because it considers only the expenses which will be booked in the current fiscal year. For the defender, the cost incurred is only from preventative and corrective maintenance for the year. For the challenger, the purchasing cost as well as the preventative and corrective maintenance costs would fall into the budget.

The challenger should ideally have no corrective maintenance costs in the first year of operation, depending on the level of use. The preventative maintenance is performed to the same level on both old and new equipment. Therefore, the difference in cost for the current year is between the corrective maintenance cost of the defender and the purchase and installation cost of the challenger.

Enumeration of Possibilities

Knapsack Problem

Once all of the information is collected, the problem is a multiple criteria decision with constraints. A problem of this type can be framed to fit several existing well known operations research problems. An operations research problem suited for this analysis is called the knapsack problem. The basic idea is there is a knapsack that can hold up to a specific amount of weight. A variety of items with different weights and values can be placed into the knapsack. Each item has its own value and weight. The goal is to get the most value in the knapsack without exceeding the weight limitations.

In this particular application, the knapsack is the budget for the current year. It is not the entire budget, only the budget remaining after assuming continuing preventative maintenance for all of the existing equipment. The items which can be placed in the budget or knapsack are abstract and represent the cost difference between the defender and challenger. The weight of the item is the cost difference between continuing maintenance on the defender and purchasing and maintaining the challenger. The value of the item is the change in reliability from the defender to the challenger. The goal is to maximize the improvement in reliability.

Fractional vs. Binary Knapsack

The knapsack problem has two forms, for items which can be partially included, referred to as the fractional knapsack problem, or for items that are indivisible, referred to as the binary knapsack problem. The other difference between the two forms is the time it takes to solve the problem, which is known as NP-Completeness. NP-Completeness is whether a particular problem can be solved in an amount of time that is proportional to a polynomial of the amount of input or 'polynomial time'. A problem that is NP-complete cannot be solved in polynomial time.

The fractional knapsack problem is not NP-Complete. The number of steps is directly proportional to the number of items to consider for placement in the knapsack. The binary knapsack is NP-Complete. To solve the problem would take 2^n steps, where n is the number of items being fit into the knapsack. Adding just one more item doubles the time to reach a solution. Adding ten more items increases the time to reach a solution by a factor of roughly 1000.

Greedy Method

A piece of equipment cannot both be maintained and replaced, meaning the problem is similar to the binary knapsack problem. To deal with the issue of scaling the problem, there are several options, two of which are considered in this project. The first is to use a method which does not attempt to explore the possibilities, but attempts to find an optimal solution quickly without thinking ahead. This is known as the greedy method, where the greedy nearsighted choice is made each time. For each piece of equipment, the ratio of the value to the weight is calculated. This is the change in the reliability over the change in cost for the current year. The list of equipment is sorted in descending order with the item with the highest ratio at the top of the list. Starting with the first item of the sorted list, if the cost of replacement fits within the budget, the item is replaced, and the overall reliability of the facilities improves as quickly as possible. If the cost of replacement does not fit within the budget, the item is skipped and the next item is considered. This is repeated until all of the items have been reviewed. The reliability is increased as fast as possible while spending the least amount of money.

Branch and Bound Method

Despite the apparent advantage of the first method, there are many possible combinations it does not consider. An alternate approach uses a branch and bound method, where the branches of possible combinations are explored and bounded by the current best estimate. The solution created using the greedy method is the starting point for the branch and bound method. The first full branch is calculated and bounded only by the size of the knapsack.

To explore the remainder of the branches, several steps are repeated over and over to reach the entire tree of possible decisions. First, starting from the last item, the decision is "undone" for every item excluded from the knapsack until an item that was included is reached. The decision for that item is then changed to exclude the item, reducing the value but regaining some portion of the weight. For each item where the decision had been "undone", the decision must be reconsidered with the additional available weight. The same logic is applied as during the first branch, where if the weight of the item does not exceed the total remaining weight it is included. Repeating these steps will explore every possible branch of the tree. This will still take 2^n steps, and not resolve the issue of scalability.

The bounding process is where the branch and bound method is able to reduce the time to reach a solution while still exploring all of the possibilities. The starting bound is the value of the first branch which is calculated using the greedy method. At each point when deciding to include or exclude an item in the knapsack for future branches, the solution using the fractional value of the branch is calculated. The fractional calculation includes the item in the same way as the binary method. However, if an item carries too much weight, a fraction of the weight is included and the same fraction of the value is added to the total value. This provides at least as good if not a better possible solution than the binary inclusion. It is, of course, unrealistic for atomic items which cannot be divided.

If the fractional value does not exceed the value of the bound, there is no need to calculate the rest of the branch. Even in the best case, the binary value of a branch will only equal the fractional value. In all other cases, the fractional value will be higher and provides an upper bound for the possible value of a branch. At any point in the process, if a complete branch is calculated and the value exceeds the current bound, the value of that branch becomes the new bound. Not only does this ensure the best solution, but it removes progressively more extraneous solutions during the calculation.

A small example of the branch and bound method with 5 items can be seen in the Figure 3.

Original Data		
Item #	**Weight**	**Value**
1	28	39
2	8	14
3	32	39
4	4	4
5	27	38

Added Value Density			
Item #	**Weight**	**Value**	**Density**
1	28	39	1.393
2	8	14	1.750
3	32	39	1.219
4	4	4	1.000
5	27	38	1.407

Sorted By Value Density			
Item #	**Weight**	**Value**	**Density**
2	8	14	1.750
5	27	38	1.407
1	28	39	1.393
3	32	39	1.219
4	4	4	1.000

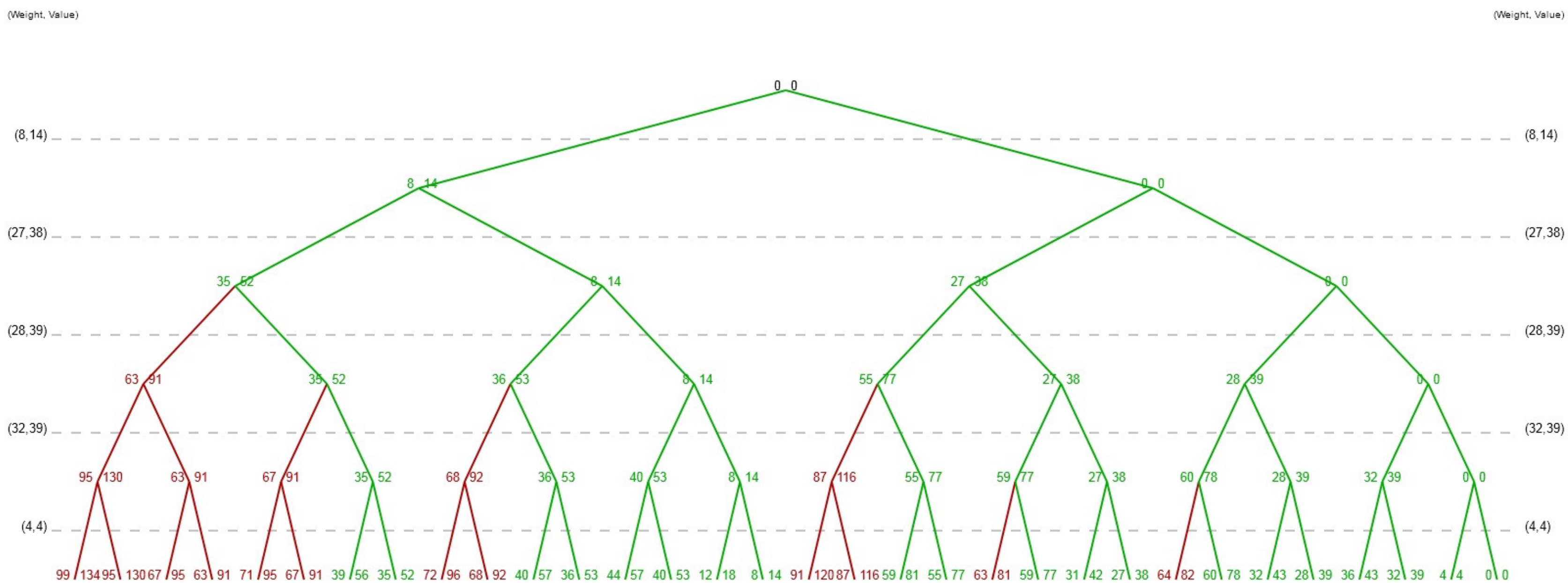

Figure 3: Branch & Bound Example

Methodology and Experimentation

Several tests were run to compare various methods of decision making to verify the improvements a decision support system would provide. Five methods of prioritization for replacement were compared. The five methods include choosing the items with the largest weight first, items with the smallest weight first, items with the largest value first, the greedy method, and the branch and bound method.

During testing, the weight represents the purchasing and installation cost of the replacement equipment. The value represents the purchasing and installation cost of the replacement equipment and the corrective maintenance cost of the existing equipment. The weight or replacement cost of the equipment is restricted to be at least $1 and no more than ¾ of the budget. The lower bound of the value is the weight and the upper bound is twice the weight.

Company X's information about equipment is not sufficient in the current format and the data is sensitive in nature. Testing was performed using randomly generated lists of 5000 pieces of equipment assuming a budget of $1,000,000. A sample of the data that was generated can be seen in Table 2 of the Appendix. This contains the first 50 pieces of equipment of the 5000 total. 30 trials with randomly generated lists were used in testing.

The generation of equipment lists was performed using Java outputting in a format ready for input into one of the five methods. Each method was implemented in a separate Java class. The output is in a comma delimited format with the run number, method, number of equipment replaced, total budget spent, and the value of the replacements. Microsoft Access was used to summarize and group the data.

Results

The overall results across all of the tests can be seen in Table 1. The full results from 30 trial runs of the experiment can be found in Table 3 in the Appendix.

Prioritization method	**Average # of Equipment Replaced**	**Average Budget Spent ($)**	**Average Value ($)**
Branch & Bound	6	999967.4	1999080.1
Greedy	9.7	999878.6	1998401.4
Largest Weight First	2.7	999927.8	1523836.4
Smallest Weight First	115.8	991569.3	1480788.4
Largest Value First	3.9	999912.1	1983012.8

Table 1: Summarized Results

From the table, the branch and bound method has the best results for the value gained, or the money saved by avoiding corrective maintenance costs and the best results in terms of spending the entire budget. The greedy method is slightly less effective in both areas, but it replaces more equipment overall.

The one method that stands out is replacing equipment prioritizing by having the smallest weight, or the lowest replacement cost. This is the least effective method in terms of avoiding corrective maintenance costs, an increase in value, and the least effective method in terms of spending the budget, an increase in weight. However, this method replaces over 100 of the 5000 pieces of equipment, significantly more pieces of equipment than any of the other methods. If the preference is to try and replace a larger number of pieces of equipment, this method may be more effective than the others.

One problem which can be seen from the data is that even if the method replacing the most equipment is used, it would take 50 years to replace all of the equipment. A clear reasoning behind this problem is during testing the cost of replacement for equipment is distributed uniformly, generated randomly between $1 and ¾ the total budget. This is a major assumption. It would be more likely that the distribution of replacement costs for equipment would be closer to a right skewed normal distribution and not uniform.

The testing also assumes all equipment on the list is being targeted for replacement. Ideally there would be less than 5000 eligible pieces of equipment for replacement each year.

One side effect of replacing the items with the smallest weight, largest weight, or largest value, is that equipment may never be selected for replacement given the prioritization. The greedy and branch and bound methods use a ratio of weight to value to ensure that equipment being replaced will be the most cost effective.

Recommendations

Company X has both areas where their process of maintenance and replacement are well developed and other areas where these processes are lacking.

Maintenance Outsourcing

One aspect that can be both beneficial and detrimental is the integration of maintenance into their business and operations. Not all companies choose this option. Instead they contract out the work to the manufacturers of equipment or vendors who specialize in maintenance. The main reason Company X has not moved to this option is the need for compartmentalization of information and secrecy. Their integrated maintenance process was put in place when they originally built the two main sites. Company X may want to reconsider this choice moving forward to be more flexible and adaptive in what equipment it purchases and maintains to win more contracts.

Fire-fighting

The fire-fighting nature of the corrective maintenance program is not beneficial for Company X. There should be a continuous feedback loop that modifies the preventative maintenance schedule based on how frequently corrective maintenance occurs. The preventative maintenance is currently selected based on the operations and maintenance (O&M) manual instructions. This may not be sufficient based on wear and use and should be adjusted to ensure that corrective maintenance is as infrequent as possible. This type of modification to the maintenance process cannot be implemented in the Maximo database management software Company X currently owns. It would have to be a manual process external to the system, though the information about the maintenance schedule adjustments should be recorded in the system.

Data Management

The two databases of maintenance information must be merged to effectively handle maintenance, maintenance management, and replacement. This is a monumental task to ensure no information is lost and the structures of both databases are maintained. Without merging the databases, data cleanliness will prevent the process from performing. The hierarchical structure of the condition assessment database would need to be removed completely.

With the databases merged, very strict standard operating procedures should be put in place and a comprehensive review of all of the information should be performed to remove dirty data. The new procedures should make sure all information is collected about incoming and outgoing equipment. Equipment that is not on the property needs to be removed. Any maintenance being performed on removed that equipment should be reviewed for validity. Every field related to the original purchase for all equipment needs to be reviewed with the corresponding procurement organization at Company X. An attempt should be made at recovering missing information for existing equipment.

System Interdependencies

A new system which identifies interdependencies between systems and redundancies should be added to the single database. This would be the most beneficial change to the databases if they are first cleaned and then merged correctly. Interdependencies would help when corrective maintenance needs to be performed, when replacement is considered, and for scheduling purposes. Redundancies in systems will play a large role in the decision to perform maintenance or replacement for high risk systems.

Equipment Reliability

The reliability assessments using facility infrastructure condition assessments from 0-5 are inadequate. The subjective nature of this score invalidates any use it might have in deciding to maintain or replace equipment. Additionally, the use of this score as one piece of the overall decision making process for replacement invalidates the process as a whole. Scores are almost always out-of-date and are not provided by the same expert each time equipment is evaluated. The same scoring is used on a wide variety of equipment which is not appropriate for all equipment. The scoring from 0-5 is not precise enough to effectively differentiate the true difference in condition, preventing the prioritization of equipment replacement. Several items with the same score may have entirely different underlying conditions. These scores should be phased out completely. This investigation used the corrective maintenance cost as an indicator of the condition, and therefore the potential to improve reliability. This is more acceptable because it provides a completely objective view of the equipment.

The potential reasons for replacing a piece of equipment are not sufficient. The only quantitative reasoning used for the current decision is the age of the equipment, which has been shown not to be an important factor in reliability. Although the program needs and strategic value of equipment is important, a strict and simple classification system for replacement of equipment would help justify decisions before considering other factors. Ideally, this would not be a subjective system but would instead be an objective classification.

This could come in the form of a decision support system which takes into account multiple pieces of information and enumerates the possible choices. This has been shown to be extremely beneficial for other companies and takes the pressure off of staff analysts to do additional manual research to show possible options. Management can change their priorities and the supporting information can be generated without any obstacles or delays.

Conclusion

The processes surrounding decision making for equipment maintenance and replacement are complex and crucial to the success of a company. There are many small well known process-related changes that can benefit any company, such as reducing fire-fighting maintenance. These changes are much easier to discuss than to implement. The most important feature of making any change is that the right data is being collected for data-driven management. Without the collection and use of data about equipment, no decision can be made using quantifiable justification. The data collected also needs to be uniform and available on all equipment.

With the data in place, a decision support system can be created to use the data without excessive workload for analysts. The proposed decision support system could be used in a variety of sensitivity analyses with different distributions of equipment. A specific method for prioritizing the replacement of equipment can be used to achieve goals for a budget. Any company could also use this method to plan budgeting for different planning horizons, to make decisions quickly on short notice, or to plan strategically over time.

Company X will directly benefit from implementing a decision support system and making the proposed changes to its processes surrounding equipment maintenance and replacement. Over time the changes will allow Company X to spend their budget more carefully, reduce costs, and post better overall performance.

References

[1] Heap, Howard F. Nowlan, F. Stanley. *Reliability Centered Maintenance*. United Airlines and the US Department of Defense. 1978. Digital Copy. Retrieved from http://reliabilityweb.com.

[2] *NASA Reliability Centered Maintenance (RCM) Guide for Facilities and Collateral Equipment*. National Aeronautics and Space Administration. September 2008. Digital Copy. Retrieved from http://www.everyspec.com.

[3] Fox, Mark S. Si Ow, Peng. Smith, Stephen F. "Constructing and Maintaining Detailed Production Plans: Investigations into the Development of Knowledge-Based Factory Scheduling Systems." *AI Magazine* 7.4(1986): 45-61. AI Magazine Archives. Web. 23 November 2011.

[4] Blanchard, Benjamin S. "An enhanced approach for implementing total productive maintenance in the manufacturing environment." *Journal of Quality in Maintenance Engineering* 3.2(1997): 69-80. Emerald. Web. 23 November 2011.

[5] Chinese, Damiana. Ghirardo, Gianni. "Maintenance management in Italian manufacturing firms." *Journal of Quality in Maintenance Engineering* 16.2(2010): 156-180. Emerald. Web. 23 November 2011.

[6] Fiori de Castro, Helio. Lucchesi Cavalca, Katia. "Maintenance resources optimization applied to a manufacturing system." *Reliability Engineering and System Safety* 91(2006): 413-420. Science Direct. Web. 23 November 2011.

[7] Ben Abdallah, Imed. ElMaraghy, Hoda. Patel, Vishvas. "A Genetic Algorithm Based Approach for Scheduling of Dual-Resource Constrained Manufacturing Systems." *Annals of the College International pour la Recherche en Productique* 48.1(1999): 369-372. CIRP Annals. Web. 23 November 2011.

[8] Wang, Kesheng. "Applying data mining to manufacturing: the nature and implications." *Journal of Intelligent Manufacturing* 18.4(2007): 487-495. SpringerLink. Web. 23 November 2011.

[9] Kaewplang, Jittra. Nagarur, Nagen N. "An object-oriented decision support system for maintenance management." *Journal of Quality in Maintenance Engineering* 5.3(1999): 248-257. Emerald. Web. 23 November 2011.

[10] Pinjala, Srinivas Kumar. Pintelon, Liliane. Vereecke, Anne. "An empirical investigation on the relationship between business and maintenance strategies." *International Journal of Production Economics* 104(2006): 214-229. Science Direct. Web. 23 November 2011.

[11] Swanson, Laura. "An empirical study of the relationship between production technology and maintenance management." *International Journal of Production Economics* 53(1997): 191-207. Science Direct. Web. 23 November 2011.

[12] Iung, B. Suhner, M.-C. Weber, P. "System Approached-Based Bayesian Network to Aid Maintenance of Manufacturing Process." *6th IFAC Symposium on Cost Oriented Automation, Low Cost Automation,* Berlin, Germany, 8-9 October 2001. 33-39. Web. 23 November 2011.

[13] Ben-Daya, M., Raouf, A. "Total maintenance management: a systematic approach." *Journal of Quality in Maintenance Engineering* 1.1(1995): 6-14. Emerald. Web. 23 November 2011.

[14] Jonsson, Patrik. "The status of maintenance management in Swedish manufacturing firms." *Journal of Quality in Maintenance Engineering* 3.4(1997): 233-258. Emerald. Web. 23 November 2011.

[15] Al-Najjar, Basim., Alsyouf, Imad. "Selecting the most efficient maintenance approach using fuzzy multiple criteria decision making." *International Journal of Production Economics* 84(2003): 85-100. Science Direct. Web. 23 November 2011.

[16] Newman, Donald G., Lavelle, Jerome P., Eschenbach, Ted G. *Engineering Economic Analysis*. Oxford University Press. New York, NY. 2009.

[17] Cormen, Thomas H., Leiseron, Charles E., Rivest, Ronald L., Stein, Clifford. *Introduction to Algorithms*. The MIT Press. Cambridge MA. 2002.

[18] Hillier, Frederick S., Liberman, Gerlad J. *Introduction to Operations Research*. McGraw-Hill. New York, NY. 2005.

[19] Garcia-Molina, Hector. Ullman, Jeffery D., Widom, Jennifer. *Database Systems: The Complete Book*. Pearson Prentice Hall. Upper Saddle River, NJ. 2009.

Appendix

Table 2: Sample Input

equipment	weight	value
1000000	5000	
1	96440	127288
2	101052	171903
3	140032	198282
4	326453	361751
5	582161	845946
6	248494	330819
7	196833	377402
8	444732	596127
9	557713	670565
10	732120	751985
11	86446	91062
12	650939	873360
13	479394	692675
14	604732	1012501
15	174408	280720
16	267443	422023
17	560459	856652
18	702857	1070469

19	165865	236543
20	161438	228243
21	503689	761750
22	533511	669677
23	378358	552209
24	115010	149843
25	331143	384698
26	464167	680611
27	498253	988048
28	303549	313472
29	607448	1097052
30	675845	805295
31	19734	22389
32	578071	666864
33	699913	1342247
34	32632	42631
35	348228	612686
36	328277	465070
37	273442	481967
38	377374	611938
39	198467	376657
40	511634	911048
41	305635	589576

42	417970	527530
43	261017	393752
44	499621	728474
45	116249	184686
46	50840	76021
47	696182	964817
48	589663	1102711
49	429320	690906
50	458029	800687

Table 3: Raw Testing Results

Overall Results				
run	**method**	**equipment**	**weight**	**Value**
0	bb	8	999987	1998694
0	greedy	13	1000000	1998094
0	largest	3	999956	1349860
0	most	110	997387	1530300
0	value	5	999983	1980139
1	bb	5	999915	1998708
1	greedy	10	999992	1997583
1	largest	2	999879	1033756
1	most	115	986881	1452956
1	value	3	999910	1989714
2	bb	6	999963	1999369
2	greedy	12	999885	1998753
2	largest	3	999990	1964543
2	most	115	999876	1520560
2	value	4	999957	1984054
3	bb	5	999921	1998846
3	greedy	7	999965	1998475
3	largest	3	1000000	1595560

Overall Results				
run	**method**	**equipment**	**weight**	**Value**
3	most	109	992826	1460570
3	value	4	999958	1970155
4	bb	6	999996	1999332
4	greedy	9	999922	1998825
4	largest	3	999998	1707248
4	most	113	996973	1518930
4	value	5	999910	1975800
5	bb	5	999967	1999113
5	greedy	8	999900	1998567
5	largest	3	999965	1700679
5	most	115	987247	1520373
5	value	3	999965	1991463
6	bb	7	999969	1998457
6	greedy	6	999733	1997986
6	largest	2	999899	1379915
6	most	110	995058	1464593
6	value	5	999959	1988741
7	bb	6	999982	1999308
7	greedy	13	999982	1997562

Overall Results				
run	method	equipment	weight	Value
7	largest	4	999975	1692191
7	most	107	987049	1470742
7	value	4	999822	1980676
8	bb	7	999974	1999215
8	greedy	10	999602	1998273
8	largest	3	999924	1673363
8	most	113	992642	1463304
8	value	5	999905	1982252
9	bb	5	1000000	1997316
9	greedy	16	999809	1996018
9	largest	3	999970	1525116
9	most	114	996188	1478409
9	value	4	999900	1981672
10	bb	9	999990	1999028
10	greedy	9	999996	1998721
10	largest	3	999992	1504623
10	most	122	993458	1478249
10	value	4	999993	1992662
11	bb	7	999968	1998623

Overall Results				
run	**method**	**equipment**	**weight**	**Value**
11	greedy	7	999676	1997875
11	largest	2	999604	1257121
11	most	119	989671	1468652
11	value	4	999906	1981677
12	bb	4	999953	1999053
12	greedy	8	999664	1998164
12	largest	3	999954	1777306
12	most	121	989076	1489617
12	value	4	999853	1961439
13	bb	4	999971	1998852
13	greedy	7	999789	1997492
13	largest	3	1000000	1271632
13	most	111	988787	1471840
13	value	4	999597	1977872
14	bb	3	999966	1999360
14	greedy	8	999887	1998880
14	largest	3	999996	1658333
14	most	125	990980	1465599
14	value	5	999968	1991887

Overall Results				
run	**method**	**equipment**	**weight**	**Value**
15	bb	6	999988	1999202
15	greedy	10	999890	1998563
15	largest	2	999961	1065076
15	most	119	994348	1476334
15	value	3	999850	1984639
16	bb	7	999992	1998740
16	greedy	12	999933	1998145
16	largest	2	999763	1493851
16	most	118	998860	1493211
16	value	3	999750	1980529
17	bb	7	999980	1999325
17	greedy	12	999940	1998091
17	largest	2	999981	1249830
17	most	125	993574	1529631
17	value	4	999974	1970825
18	bb	9	999989	1998892
18	greedy	10	999798	1998578
18	largest	4	999709	1649016
18	most	119	989298	1466656

Overall Results				
run	method	equipment	weight	Value
18	value	4	999865	1991054
19	bb	4	999989	1999501
19	greedy	11	999900	1999031
19	largest	3	999953	1689017
19	most	120	995861	1494084
19	value	3	999965	1983436
20	bb	5	999977	1999594
20	greedy	8	999861	1999044
20	largest	2	999908	1860800
20	most	111	983159	1460115
20	value	3	999928	1984938
21	bb	6	999976	1999561
21	greedy	8	999876	1999116
21	largest	3	999969	1382353
21	most	123	995841	1482504
21	value	4	999986	1984841
22	bb	5	999941	1999644
22	greedy	5	999941	1999644
22	largest	2	999988	1671521

Overall Results				
run	method	equipment	weight	Value
22	most	110	986888	1503283
22	value	4	999973	1990010
23	bb	7	999957	1999715
23	greedy	12	999824	1998609
23	largest	3	999941	1750826
23	most	116	989556	1437054
23	value	4	999953	1989308
24	bb	8	999887	1998848
24	greedy	8	999887	1998848
24	largest	3	999973	1288165
24	most	117	991457	1500002
24	value	4	999851	1987270
25	bb	6	999930	1998987
25	greedy	10	999996	1998644
25	largest	2	999919	1654236
25	most	112	986164	1467682
25	value	4	999935	1986613
26	bb	7	999914	1999008
26	greedy	13	999999	1998623

Overall Results				
run	method	equipment	weight	Value
26	largest	3	999937	1310624
26	most	113	981816	1414630
26	value	3	999875	1992527
27	bb	5	999983	1999510
27	greedy	10	999994	1998840
27	largest	3	999769	1719629
27	most	115	992688	1536608
27	value	4	999936	1972187
28	bb	5	999998	1999481
28	greedy	9	999820	1998595
28	largest	3	999991	1321994
28	most	119	984372	1430967
28	value	2	999938	1970333
29	bb	6	1000000	1999121
29	greedy	10	999898	1998404
29	largest	2	999971	1516909
29	most	118	999099	1476196
29	value	5	999998	1991671